

## C<sub>2</sub>: An asymmetric specie ?

Robson Fernandes de Farias

Universidade Federal do Rio Grande do Norte, Cx. Postal 1664, 59078-970,  
Natal-RN, Brasil. [robdefarias@yahoo.com.br](mailto:robdefarias@yahoo.com.br)

### Abstract

The present work is another contribution to a better understanding of the chemical bond in C<sub>2</sub>. Several density functional approach/basis set provided calculated IR and Raman spectra with simultaneous active bands. Hence, the hypothesis of electronic asymmetry in C<sub>2</sub> [1] was reinforced.

*Keywords:* C<sub>2</sub>, chemical bonding, IR spectra, Raman spectra.

## Introduction

Although not a stable (isolable) specie,  $C_2$  is of great practical importance, being present, for example, in the blue flame resulting from the combustion of hydrocarbons. From a theoretical point of view,  $C_2$  is a real challenge given the intriguing and even enigmatic nature of the chemical bond in this molecule, and according to Hoffmann, it epitomizes many of the fundamental questions of chemistry [1].

After all,  $C_2$  exhibits a double, triple or quadruple bond ? The last possibility seems, at a first looking, the less probable one, since carbon has not (as Cr, for example) suitable  $d$  orbitals to form a  $\delta$  bond.

In a previous work [2],  $C_2$  was modelled by using a density functional approach, and it was verified that the calculated bond distance and bond dissociation energies were in very good agreement with the previously [3-6] valence bond results. Furthermore, the obtained results also points to a bond order of four, reinforcing previously obtained data [5,6]. Hence, based on the calculated IR and Raman spectra, was proposed that  $C_2$  exhibits, at an electronic level, an asymmetry, and that such molecule has not, in fact, a centre of inversion. This last hypothesis needs, of course, to be well explored.

The present work is another contribution to a better understanding of the chemical bond in  $C_2$  and expands the previous one [2]. Its main goal is to verify if the hypothesis of an electronic asymmetry in  $C_2$  could be proved. .

## Methodology

$C_2$  molecule was modelled by density functional (DFT) approach. The specifically employed bases set are summarized in Table 1. For all calculations,  $C_2$  was modelled with zero charge and zero unpaired electrons.

## Results and discussion

As can be verified from Table 1 data, the DF-  $\omega$ B97X-D/6-31+G\* theoretical approach provides a bond dissociation energy ( $\text{kJ mol}^{-1}$ ) calculated value of 593.40, only 3.2% below the available experimental value of  $613.08 \pm 0.25$  [2]. Such fact, as well a bond order close to four, in agreement with previous calculated data, reinforced the hypothesis of a quadruple bond in  $\text{C}_2$  [2,5,6].

As can also be verified from Table 1 data, the calculated bond distance and bond order can be very different, depending on the employed theoretical approach. Of course, this is not a surprise, as is well known that different theoretical approach can exhibit different strong and weak points: some are well succeeded to calculate bond energies but not calculate another properties, some works well for light species but not to heavy ones, etc. Of course, in such cases, experimental data are always the “touchstone”, since nature always has the last word. Furthermore, the agreement between the calculated data and another ones, obtained by other researchers employing different theoretical approach is also a possible way to validation.

However, taking into account the elusive nature of the chemical bond in  $\text{C}_2$ , how can one be sure about how is the right/reliable/trustable theoretical approach to be employed, and hence, how high is the reliability of the calculated data ?

As previously reported [2] DF-  $\omega$ B97X-D/6-31+G\* and DF-  $\omega$ B97X-D/6-311+G\*\* approach have provided support to a bond order of four and trustable bond energy values, with good bases on experimental and theoretical data [2-6]. However, as also previously noted [2]  $\text{C}_2$  belongs to the  $D_{\infty h}$  point group. Such point group has an inversion centre as symmetry element and, as is well known, a molecule that has a vibrational mode active simultaneously in IR and Raman cannot have an inversion centre. Nevertheless, simultaneously active IR and Raman bands were calculated for  $\text{C}_2$  [2]. Hence, was proposed that  $\text{C}_2$  has not an inversion centre, with the and asymmetry between the two carbon atoms

been explained at an electronic level, that is, from a geometrical point of view,  $C_2$  has an inversion centre ( $D_{\infty h}$  point group) but, at an electronic level, there is an asymmetric distribution of electrons. It was supposed that such asymmetric electronic distribution could even be a slight one, not enough to change, in a measurable amount, the dipole moment. .

As can be verified by Table 1 data and Figure 1, DF- SOGGA11-X/6-31G\*, DF- M06-2X/6-311-G\*\* and DF-B97-3/6-311-G\*\* approach provides very intense calculated IR and Raman bans, simultaneously active. Hence, the hypothesis of electronic asymmetry is reinforced (proved ?).

The calculated Mulliken and Löwdin bond orders are 2.43 and 2.84, respectively, in excellent agreement with the photoelectron spectroscopy experimental data obtained in 2019 by Laws et al [7], which concludes that “this result suggests that the dominant contribution to the dicarbon bonding involves a double-bonded configuration, with  $2\pi$  bonds and no accompanying  $\sigma$  bond.” Our present calculations, supported by such experimental data [7] of course contradicts the hypothesis of a fourth order bond.

The DF-B3PW91/6-311+G\*\* approach provides higher bond orders, but an inconsistent bond energy of only  $136 \text{ kJmol}^{-1}$ .

As a preliminary finding, I can say that my previous study [2] supports a quadruple bond to  $C_2$  and that the present one supports a double (or triple) bond ?

In order to “keep the eye in the ball”, lets return to the safe territory of bond dissociation energy ( $\text{kJmol}^{-1}$ ) values [9]:  $H_3C-CH_3$ ,  $377.4 \pm 0.8$ ;  $H_2C=CH_2$ ,  $728.4 \pm 6.3$  and  $CH\equiv CH$   $960.2 \pm 4.2$ . hence, taking into account these values and the value reported in Table 1 to the chemical bond in  $C_2$ , it is necessary to conclude that the bond in  $C_2$  is closer to a double, not triple or quadruple bond.

Another “safe territory” is the bond lengths: C-C, 153 pm; C=C 134 pm and  $C\equiv C$  120 pm [10]. Once again, can be concluded that the carbon-carbon bond in  $C_2$  is about “two and half”.

Such conclusions, besides the experimental validation mentioned [7] is also support by the theoretical investigation (magnetic shielding studies) of Karadakov and Kirsopp [8] which conclude that “dicarbon has less total electron density than ethyne along and around the carbon-carbon bond”.

Hence, the only “constant” present for all calculated data is the simultaneously active IR and Raman bands (sometimes both as very strong bands, sometimes the IR band is very weak and appears only in the table of calculated bands, not in the “drawn” spectra). Hence, so far I can see, the present study reinforces the hypothesis of an asymmetry (at an electronic level) for  $C_2$ .

Based on the results obtained here, as well as literature data [1-9], some conclusion can be pointed out:

- a) For  $C_2$  both, bond distance and bond dissociation energy are compatible with a double or “2 ½” bond. Such facts are also reinforced by other experimental and theoretical data;
- b) The facts pointed in (a) are not in contradiction with the bond order 3 or 4, calculated in many works: the third and fourth bonds are extremely weak if compared with the “conventional” double bond and hence, have a little effect on the bond distance and energy; Some theoretical approach (due to their physical-mathematical idiosyncrasies) can “detect” such third and fourth bond, some cannot. That’s all;
- c) As shown on the present work, many theoretical approach allows to calculate for  $C_2$  IR and Raman bands simultaneously active (in many cases, both IR and Raman band are very intense), suggesting that an electronic level  $C_2$  is not a symmetrical specie;
- d) Nevertheless, at the present point it is not possible (?) to be sure if such asymmetry is a real physical fact or if the simultaneity of the IR and Raman band are not only an error due to the physical-mathematical idiosyncrasies of the employed theoretical approach.

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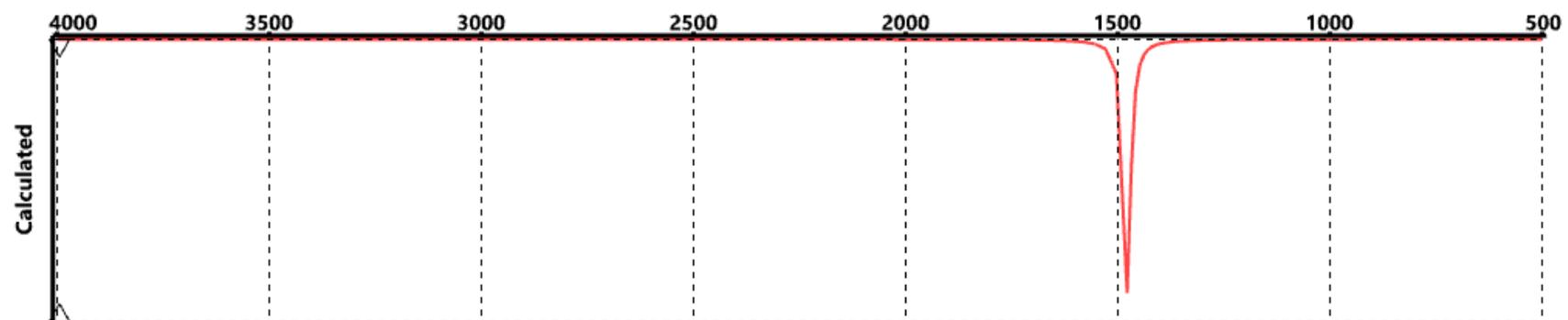
## Captions of figures

Figure 1. Calculated infrared (a) and Raman (b) spectra to  $C_2$  (DF- SOGGA11-X/6-31G\*).

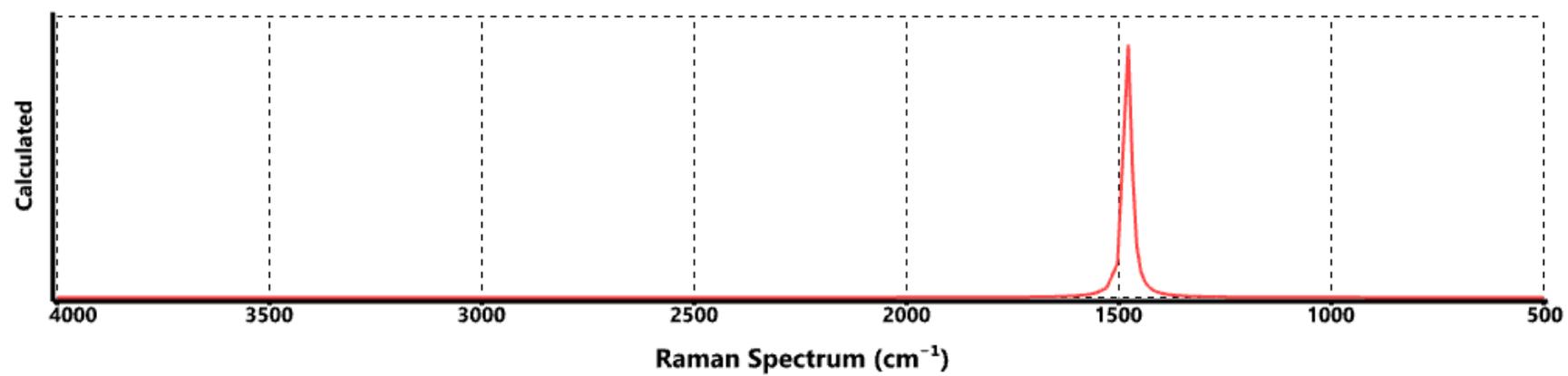
Table 1. Summary of the calculated parameters to C<sub>2</sub> (modelled with charge and zero unpaired electrons).

Theoretical approach	Bond distance /pm	Mulliken bond order	Löwdin bond order	Bond dissociation energy/kJmol <sup>-1</sup>	IR bands /cm <sup>-1</sup>	Raman bands /cm <sup>-1</sup>
DF- ωB97X-D/6-31+G* [Ref. 2]	125.4	3.42	3.66	593.4 (613.08±0.25) <sup>#</sup>	1906 <sup>vw</sup>	1906 <sup>vs</sup>
DF- ωB97X-D/6-311+G** [Ref. 2]	125.1	3.55	3.97	584.7	1886 <sup>vw</sup>	1886 <sup>vs</sup>
DF- SOGGA11-X/6-31G*	137.9	2.43	2.84	326.2	1478 <sup>vs</sup>	1478 <sup>vs</sup>
DF-B3PW91/6-311+G**	139.0	3.09	3.57	136.0	1435 <sup>vw</sup>	1435 <sup>vs</sup>
DF- M06-2X/6-311-G**	124.9	3.53	3.96	444.8	1894 <sup>vs</sup>	1894 <sup>vs</sup>
DF-B97-3/6-311-G**	138.7	2.83	3.37	201.6	1451 <sup>vs</sup>	1451 <sup>vs</sup>

<sup>#</sup>Experimental value, Ref. 3; vw = very weak; s = very strong.



(a)



(b)

Figure 1